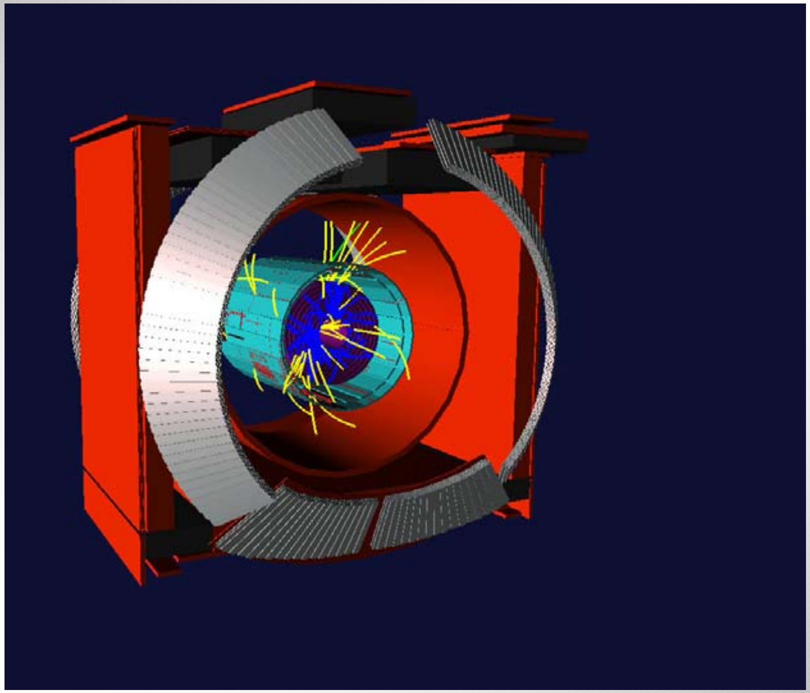
Higgs Physics : The origin of mass



Marcela Carena

Physics for Everyone

Fermilab, April 2, 2002.

The Forces of Nature

- Why are the four forces in nature so different?
- How do we try to model them?

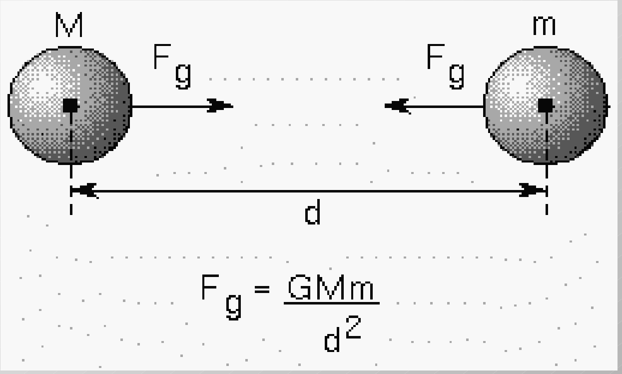
The Fundamental Particles

- quarks and leptons (matter), and gauge bosons (force carriers)
- How do they get mass?
- How do we test the mechanism for the origin of mass ?

Gravitational and electromagnetic interactions

- Gravity

Attractive force between 2 massive objects:



Is very weak unless one of the the masses is huge, like the earth

- Electromagnetism

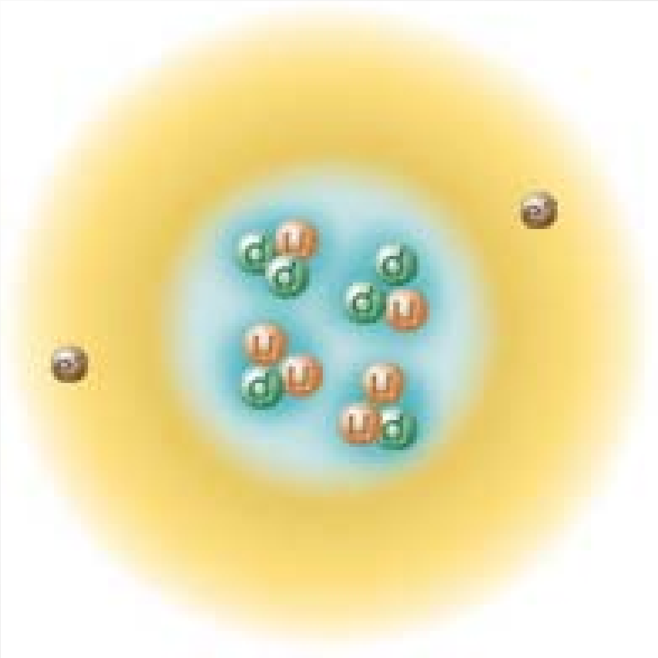
Electrons colliding in the screen!

Electrons interact with protons

Via quantum of e.m. energy

the photons

Strong Interactions



Atoms are made from
protons, neutrons and electrons

Smashing electrons with protons or neutrons at high energies shows that protons and neutrons are not fundamental

p → u u d

formed by three quarks, bound together by the gluons of the strong interactions

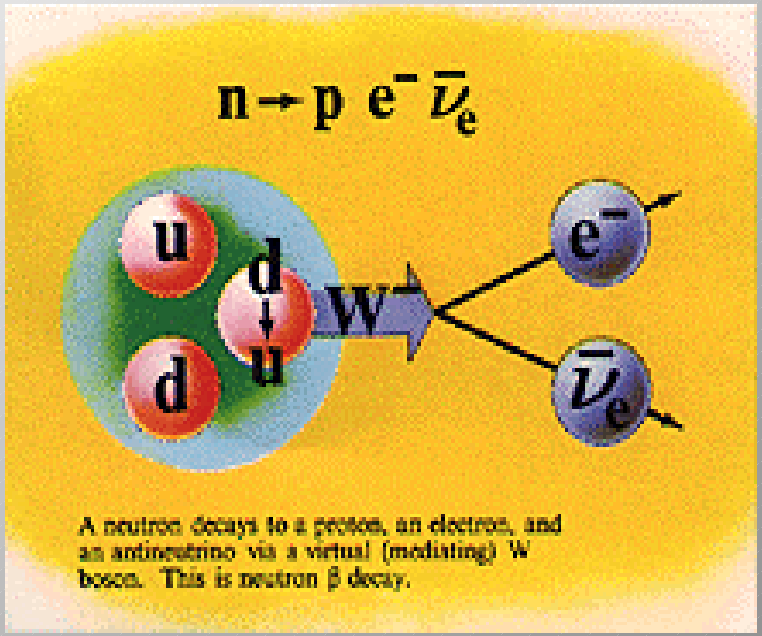
n → u d d

Weak Interactions

Observation of Beta decay

↓

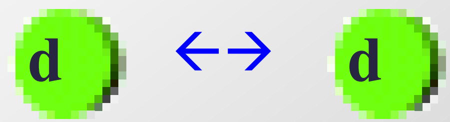
demanded a novel interaction



Short range forces only existent inside the protons and neutrons, with massive carriers:

gauge bosons: W and Z

How strong is strong?



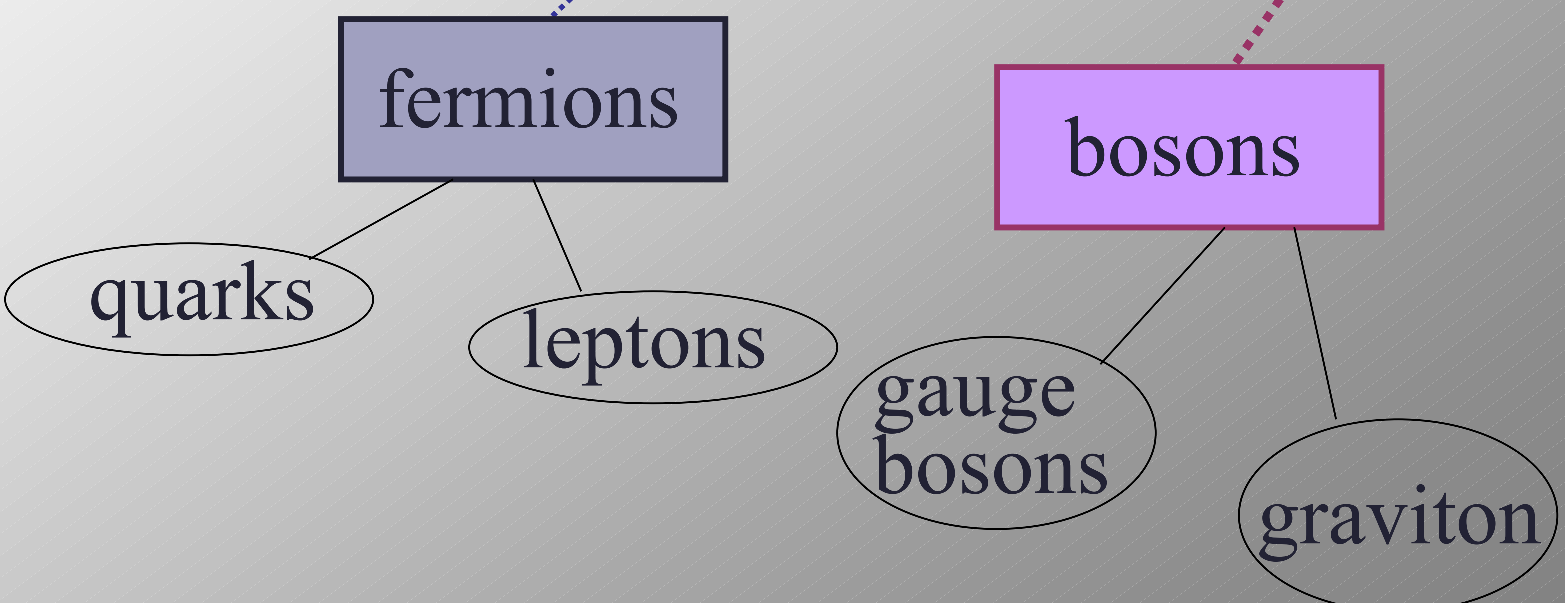
- 100 times stronger than the electromagnetic repulsion

- 100,000 times stronger than the weak force

- 100 trillion trillion trillion times stronger than the Gravitational attraction

The Complete Picture

The universe is made out of matter particles and held together by force particles



LEPTONS

QUARKS

GAUGE BOSONS

$$\begin{bmatrix} \nu_e \\ e \end{bmatrix}_L \quad \begin{matrix} \boxed{\nu_e} \\ R \\ \boxed{e} \end{matrix} \qquad \begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}_L \quad \begin{matrix} \boxed{\nu_\mu} \\ R \\ \boxed{\mu} \end{matrix} \qquad \begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix}_L \quad \begin{matrix} \boxed{\nu_\tau} \\ R \\ \boxed{\tau} \end{matrix}$$

QUARKS

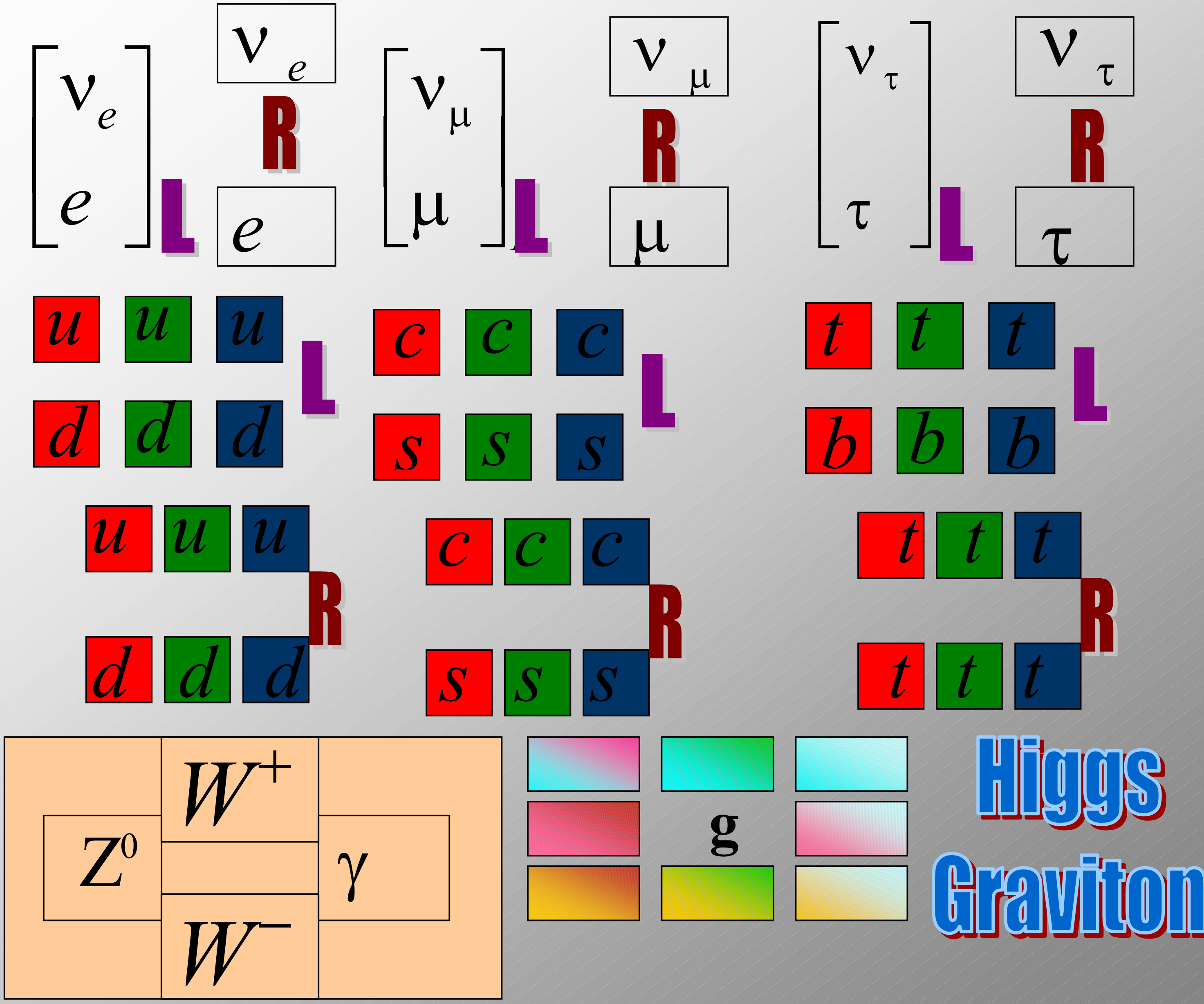
GAUGE BOSONS

$\begin{bmatrix} \nu_e \\ e \end{bmatrix}_L$ $\quad \begin{matrix} \boxed{\nu_e} \\ R \\ \boxed{e} \end{matrix}$ $\quad \begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}_L$ $\quad \begin{matrix} \boxed{\nu_\mu} \\ R \\ \boxed{\mu} \end{matrix}$ $\quad \begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix}_L$ $\quad \begin{matrix} \boxed{\nu_\tau} \\ R \\ \boxed{\tau} \end{matrix}$

$\begin{matrix} u & u & u \\ d & d & d \end{matrix} \; L \qquad \begin{matrix} c & c & c \\ s & s & s \end{matrix} \; L \qquad \begin{matrix} t & t & t \\ b & b & b \end{matrix} \; L$

$\begin{matrix} u & u & u \\ d & d & d \end{matrix} \; R \qquad \begin{matrix} c & c & c \\ s & s & s \end{matrix} \; R \qquad \begin{matrix} t & t & t \\ t & t & t \end{matrix} \; R$

GAUGE BOSONS



ν_e e L
ν_e R e
ν_μ μ L
ν_μ R μ
ν_τ τ L
ν_τ R τ
u u u d d d L
c c c s s s L
t t t b b b L
u u u R d d d
c c c R s s s
t t t R t t t
W^+ Z^0 γ W^-
g
Higgs
Graviton

The Standard Model:

A model or a theory ?

A model is a mathematical structure that makes a number of predictions that can be tested experimentally or that provides a good explanation for experimental observations.

Once the mathematical structure provides a well-tested and well-established understanding of an underlying mechanisms or process it becomes a theory.

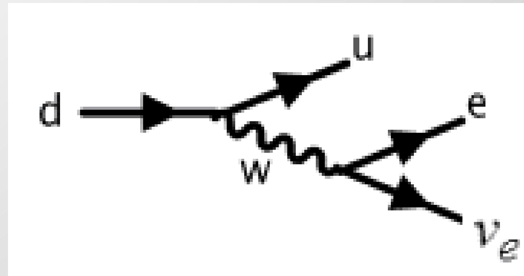
the Standard Model

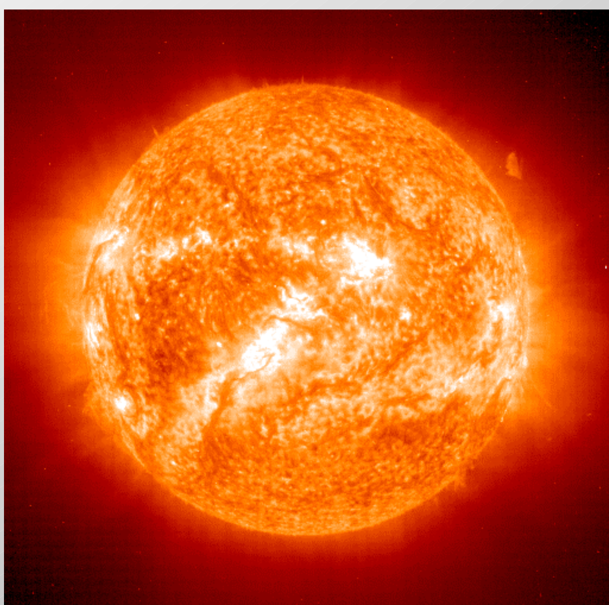
A Quantum Theory that successfully describes how all known fundamental particles interact via the strong, weak and electromagnetic forces

It has been tested with very high precision (one part in a thousand!

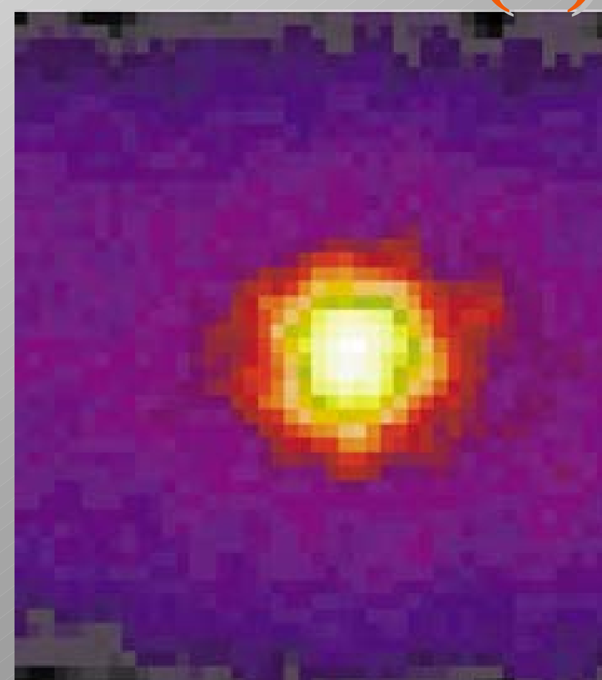
at experiments around the world
CERN, Fermilab, SLAC

The Standard Model explains nearly everything!

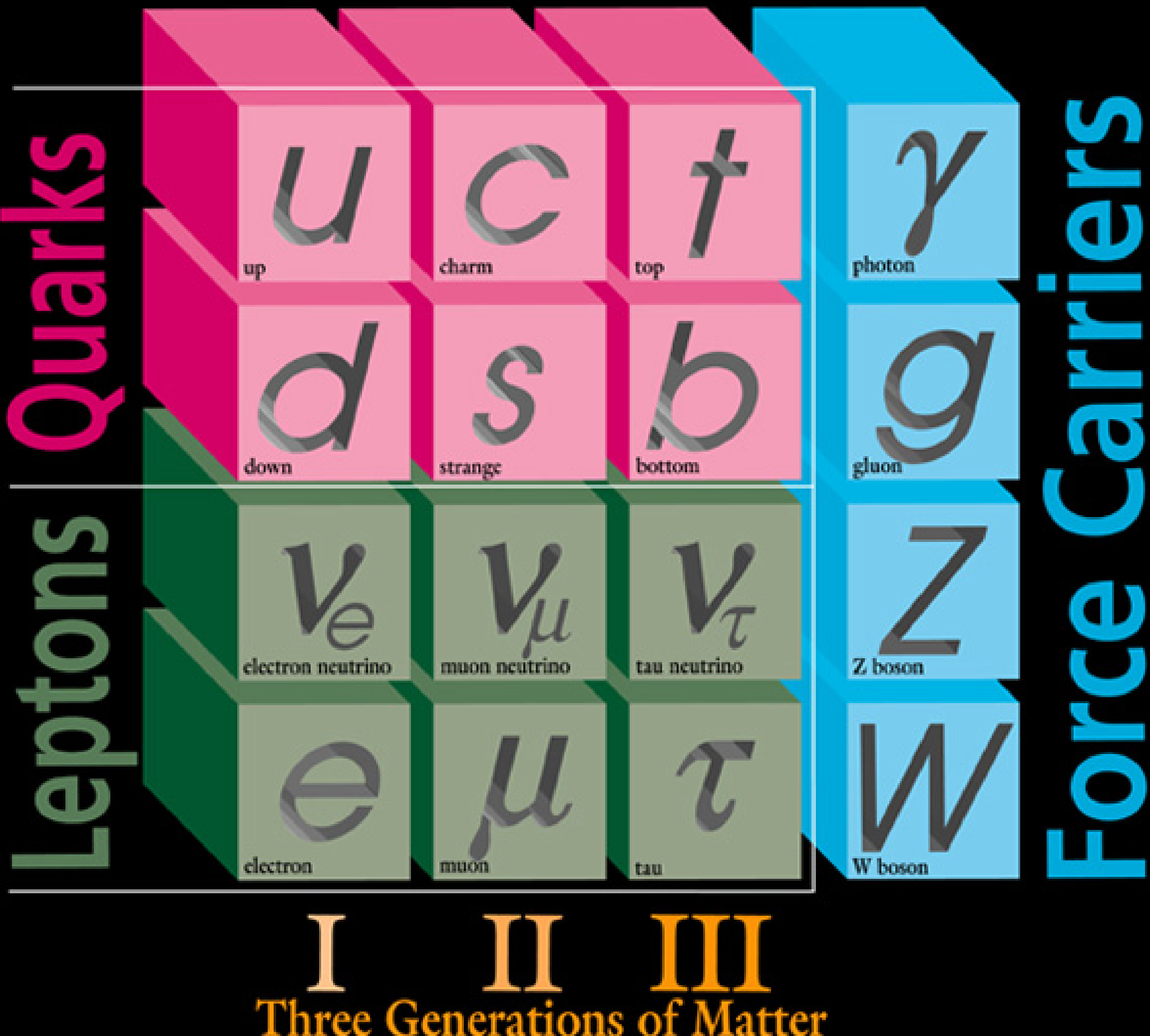




neutrino (ν) sky



ELEMENTARY PARTICLES



Matter: **3 families of quarks and leptons have the same properties (quantum numbers) under the symmetries of nature**

BUT they have very different masses

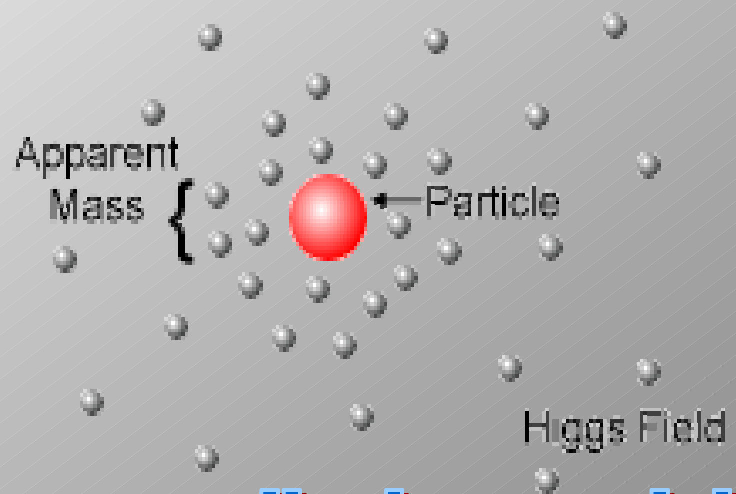
- the electron has a mass of one part in a 1000 trillion trillion grams
- the muon is about 200 times heavier than the electron
- top quark is about 350,000 times heavier than the electron

Crucial Problem:

The symmetries of the model do not allow for a mechanism to generate mass at all!

The Standard Model holds together only postulating the existence of a special field of energy which permeates all of the space

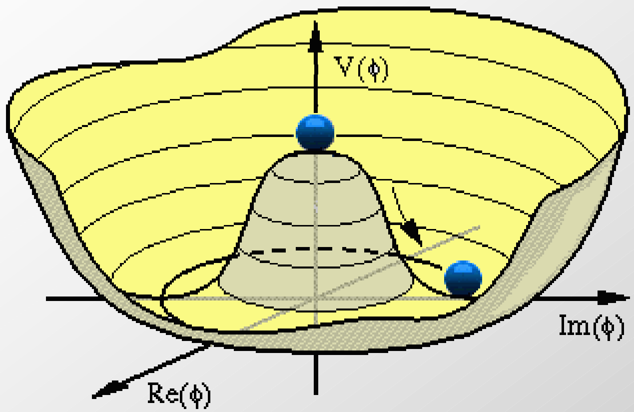
The Higgs Field



and serves as source of mass to all other particles

Without the field's energy, the particles would theoretically weighed nothing → description would be useless

The Higgs Mechanism



The Higgs field prefers to acquire a nonzero value to minimize its energy

Spontaneous Breakdown of the symmetry

vacuum becomes a source of energy = a source of mass

In quantum field theory

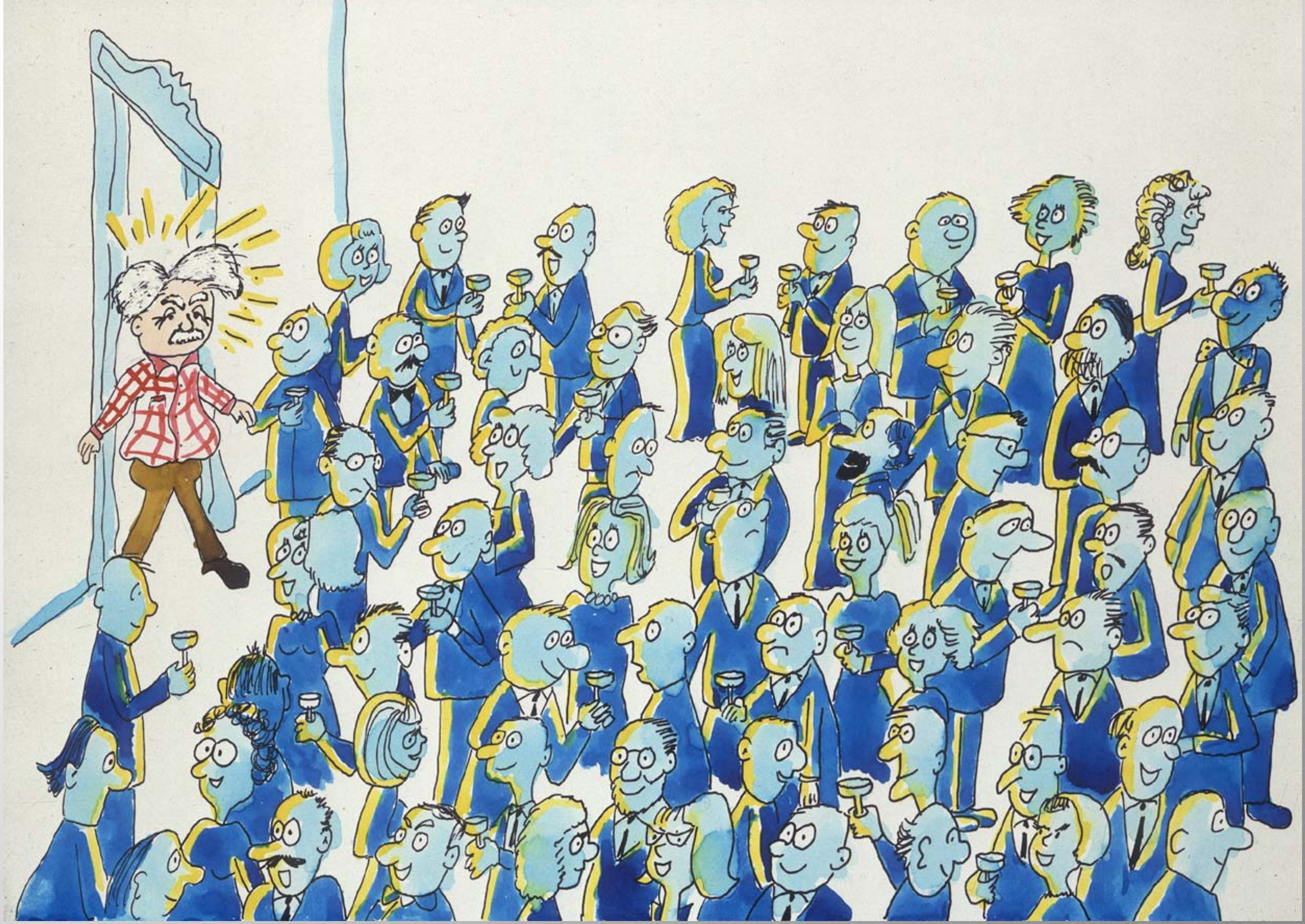
fields are associated with particles

Higgs Fields → Higgs Boson particle

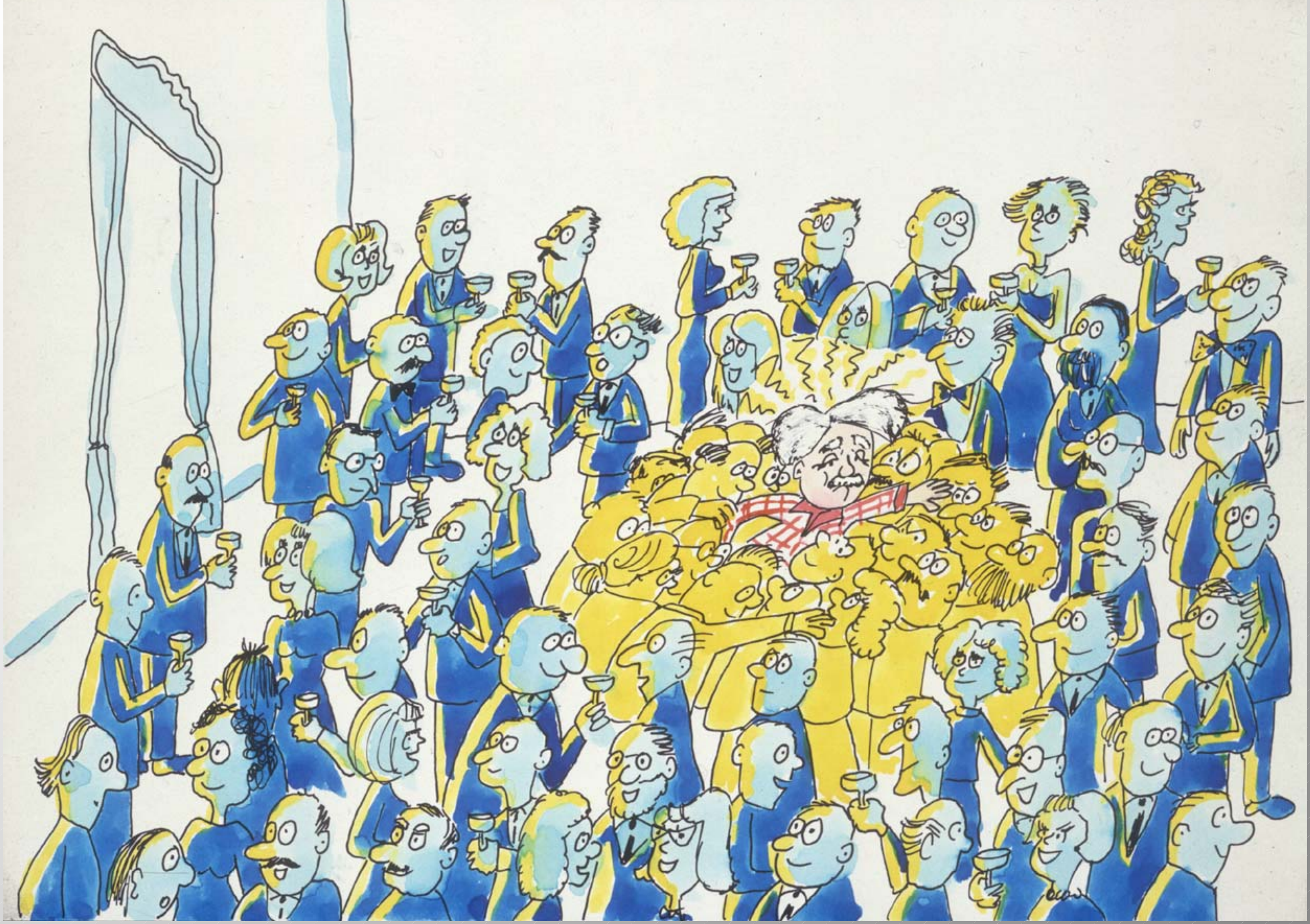
The Higgs Mechanism

As a cartoon

To understand the Higgs Mechanism imagine that a room full of physicicists quietly chattering is like space filled only with The Higgs field...



A well known scientist walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step



This increase his resistance to movements, in other words, he acquires mass, just as a particle moving through the Higgs field ...

If a rumour crosses the room......

It creates the same type of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.

All fundamental particles but one have been seen at accelerators

The missing particle of the Standard Model

THE HIGGS BOSON

Is quite essential

finding the Higgs boson is the key to discover if the Higgs field exist, and hence to prove if our simplest explanation for the origin of mass is indeed correct.

Although the Higgs boson has not been measured

the high precision tests of the Standard Model probe the indirect effects of the Higgs field through the values of SM observables :

particle masses, decay rates, etc

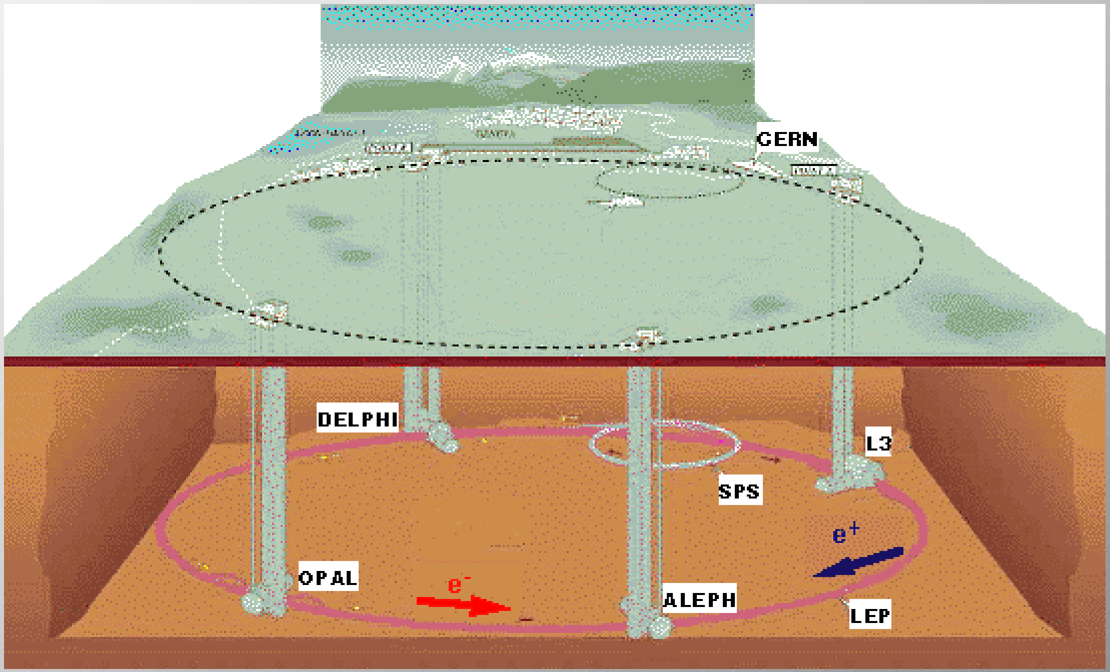
As a result, from present experimental data

the mass of the Higgs boson is expected to be lighter than about 200 protons

proton mass → one part in a trillion trillion grams

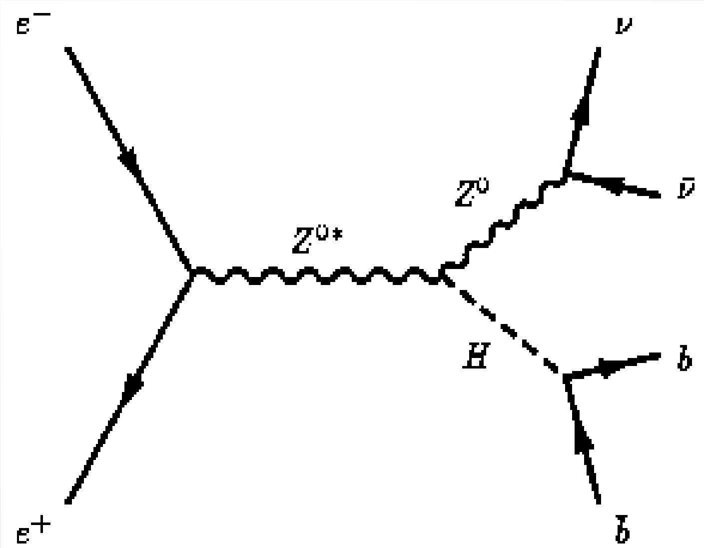
The Search for the Higgs Boson

- **At The Large Electron Positron Collider - LEP**



Bunches of electron and positrons traveling at very high speed in opposite directions, collide creating burst of high energy which rematerialises as subatomic particles

If the Higgs Boson is created , it will decay rapidely into other particles



At LEP energies mainly into pairs of b quarks

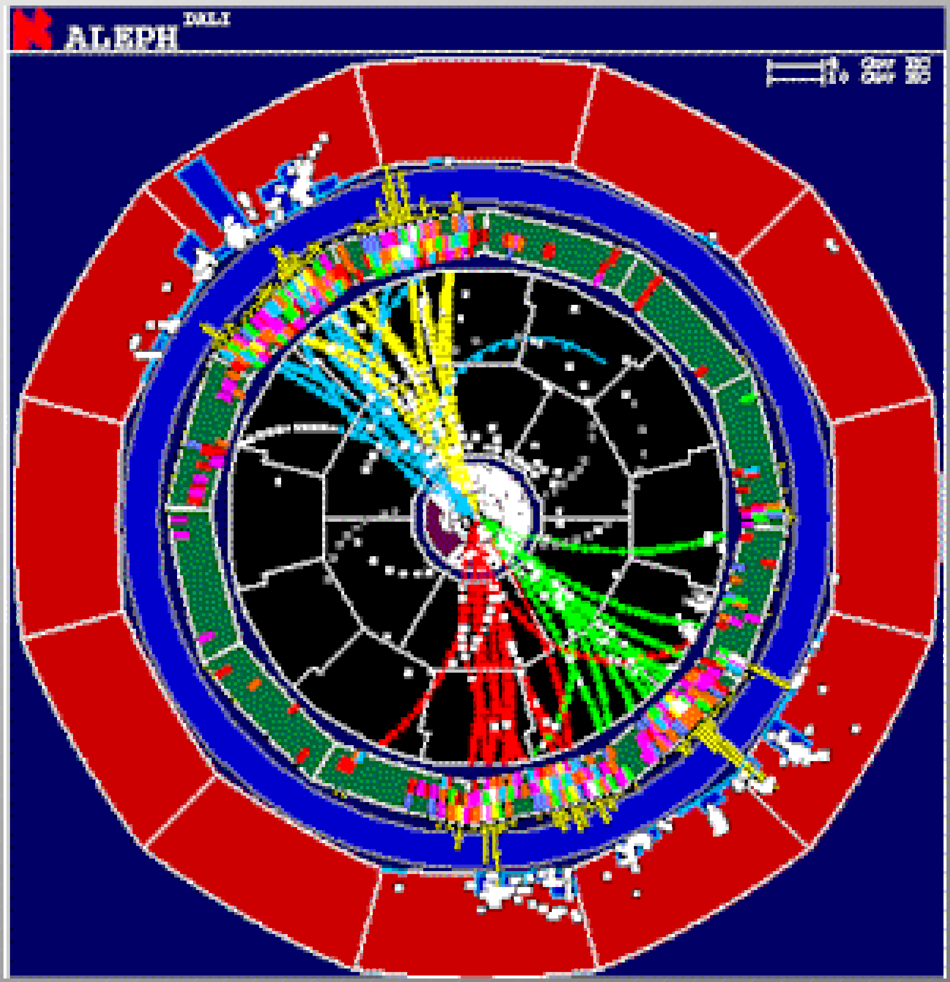
One detects the decay products of the Higgs and the Z bosons

LEP Run is over

- No Higgs seen with a mass below 114 GeV
- But, tantalizing hint of a Higgs with mass about 115 -- 116 GeV (just at the edge of LEP reach)

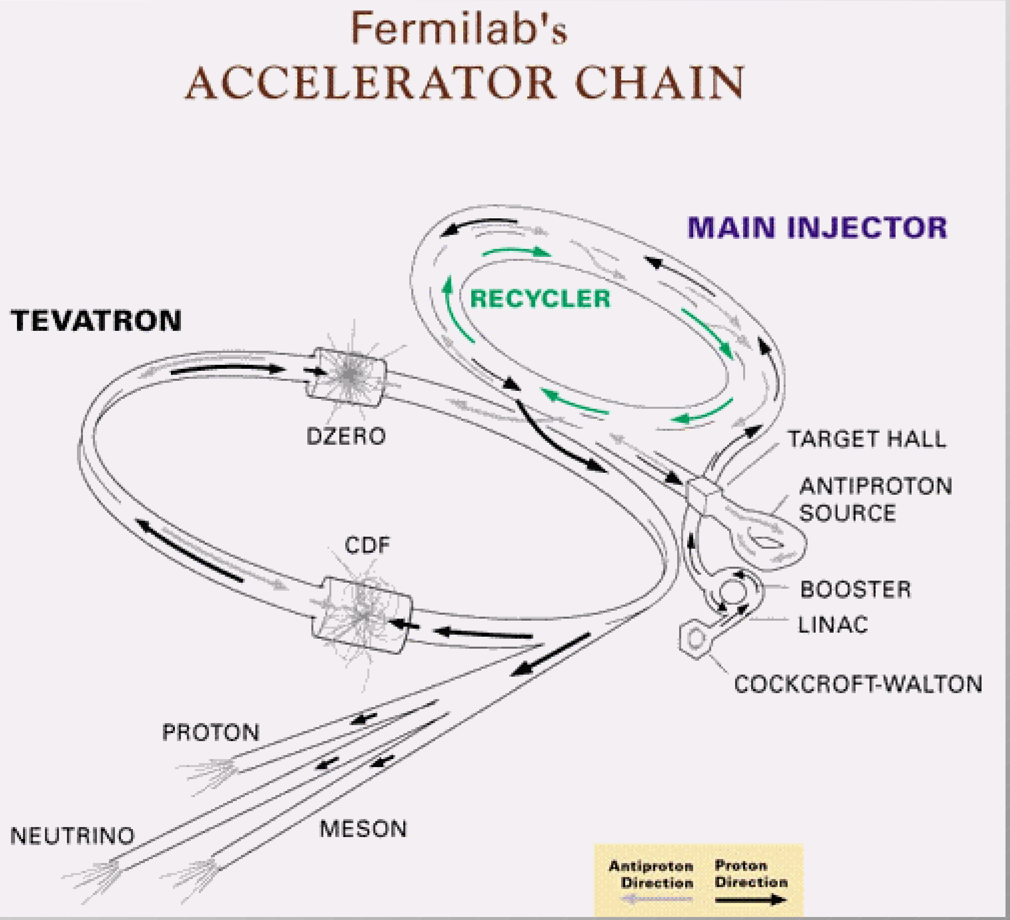
Higgs Particle Search at LEP (Aleph detector)

Higgs candidate with mass of about 114 +- 3 GeV and three identified b quarks

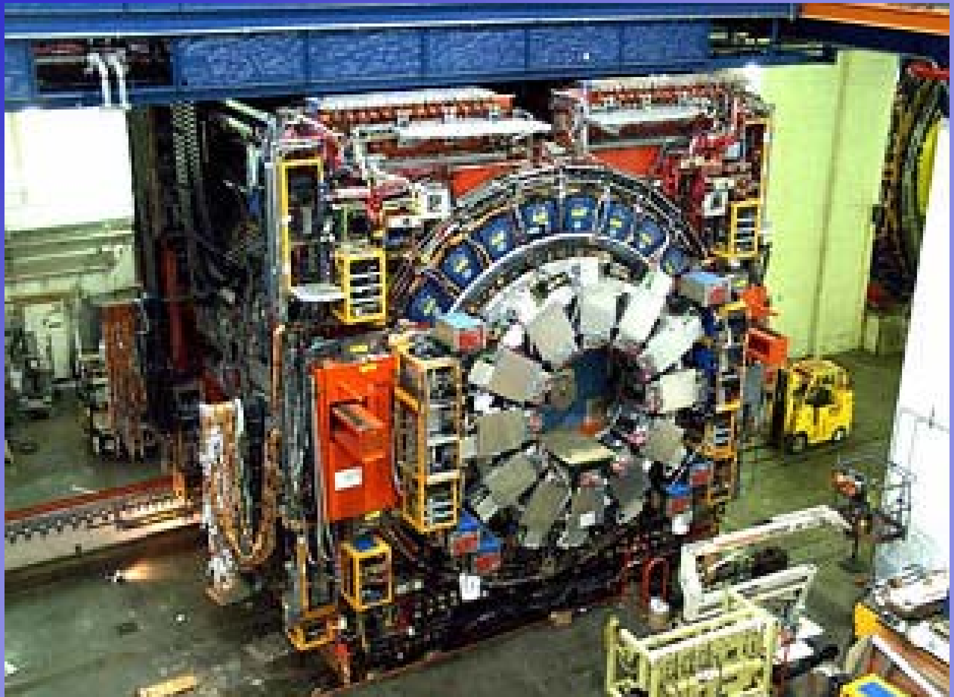


Next chance to reveal mechanism that can explain the origin of mass in nature → here at Fermilab!

The Tevatron Run 2



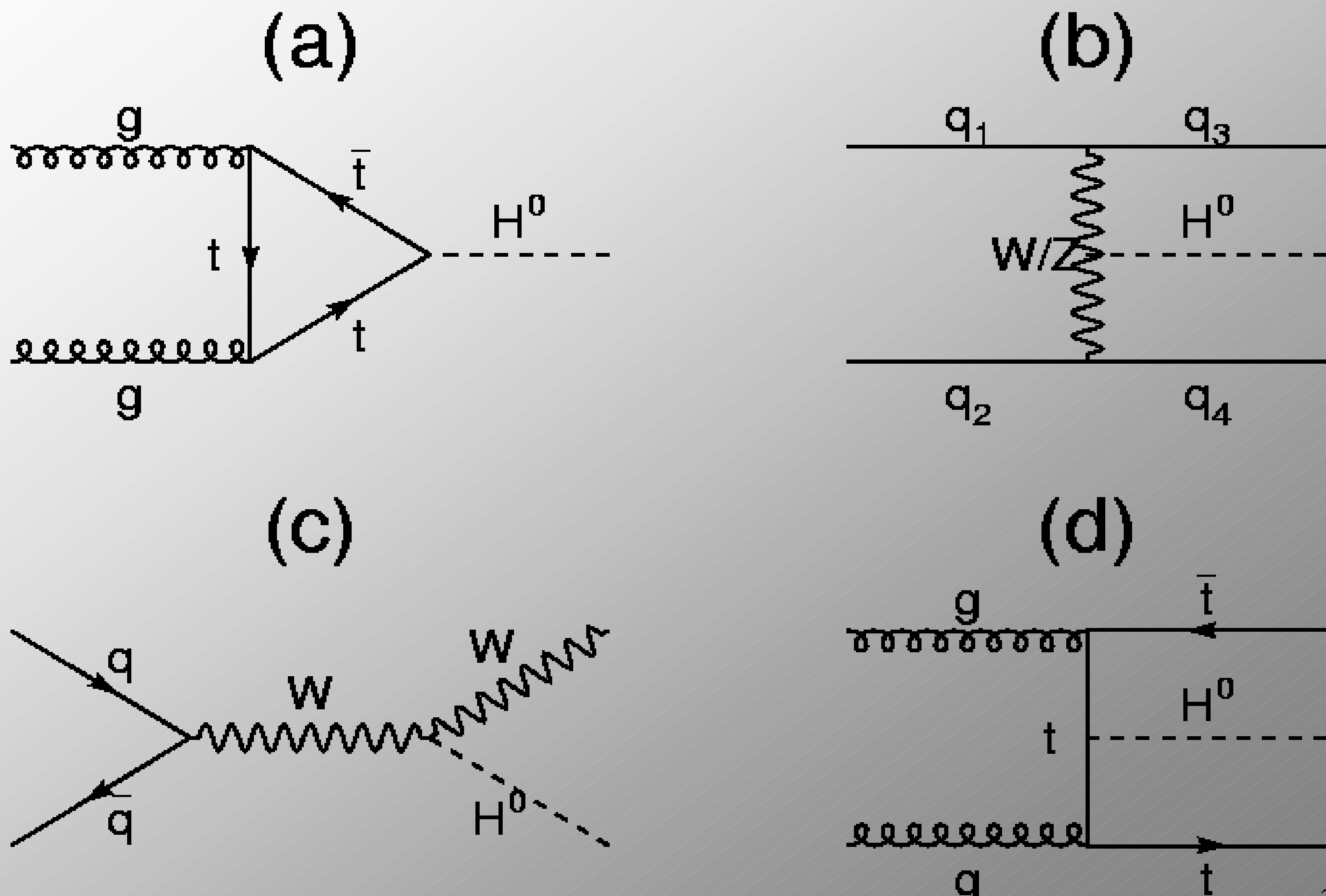
Protons and antiprotons (quark and antiquark or two gluons) collide, and if the collision is energetic enough, shower of particles will be produced



CDF Detector

D0 Detector

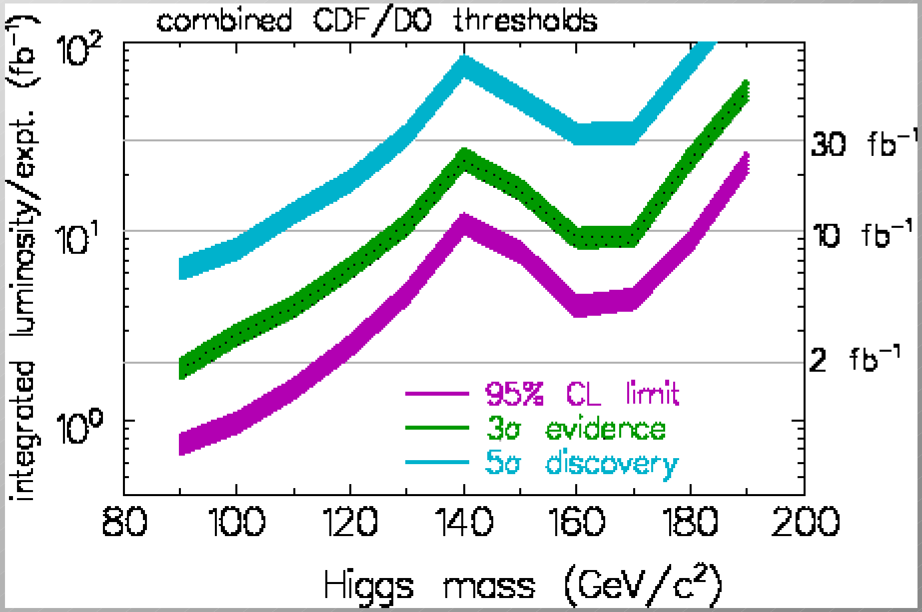
Higgs production processes at hadron colliders



At Fermilab we can search for Higgs bosons with mass as large as about 200 protons (200 GeV)

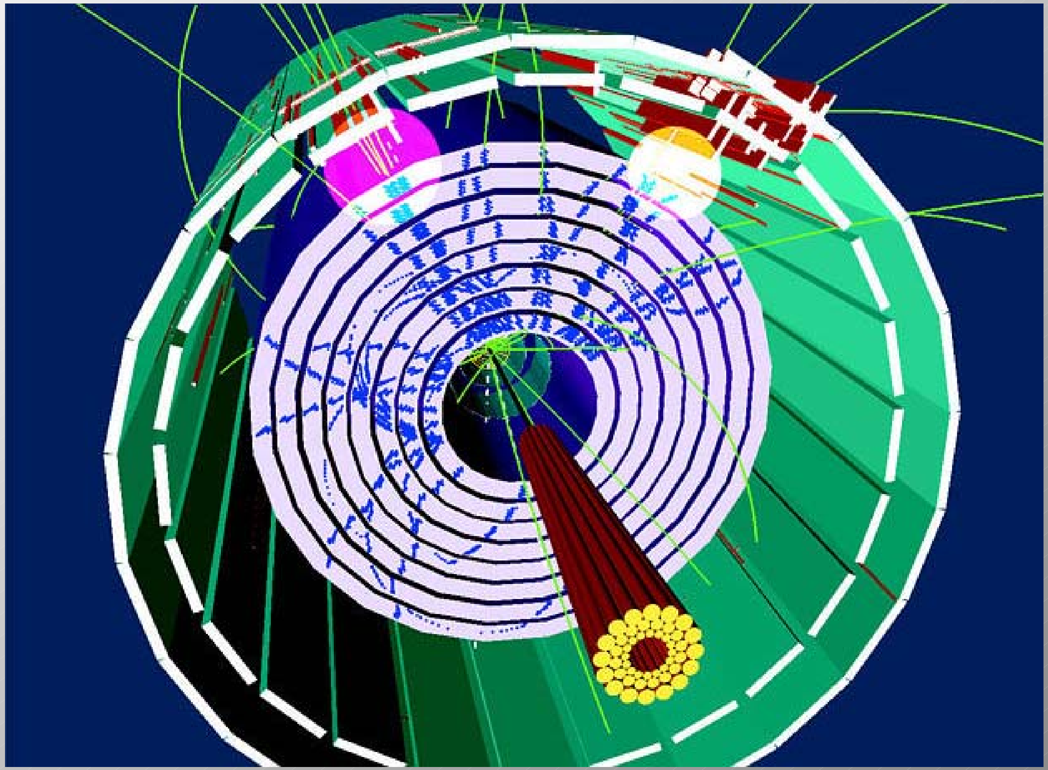
This is the preferred range from precision data !

But it will not be easy



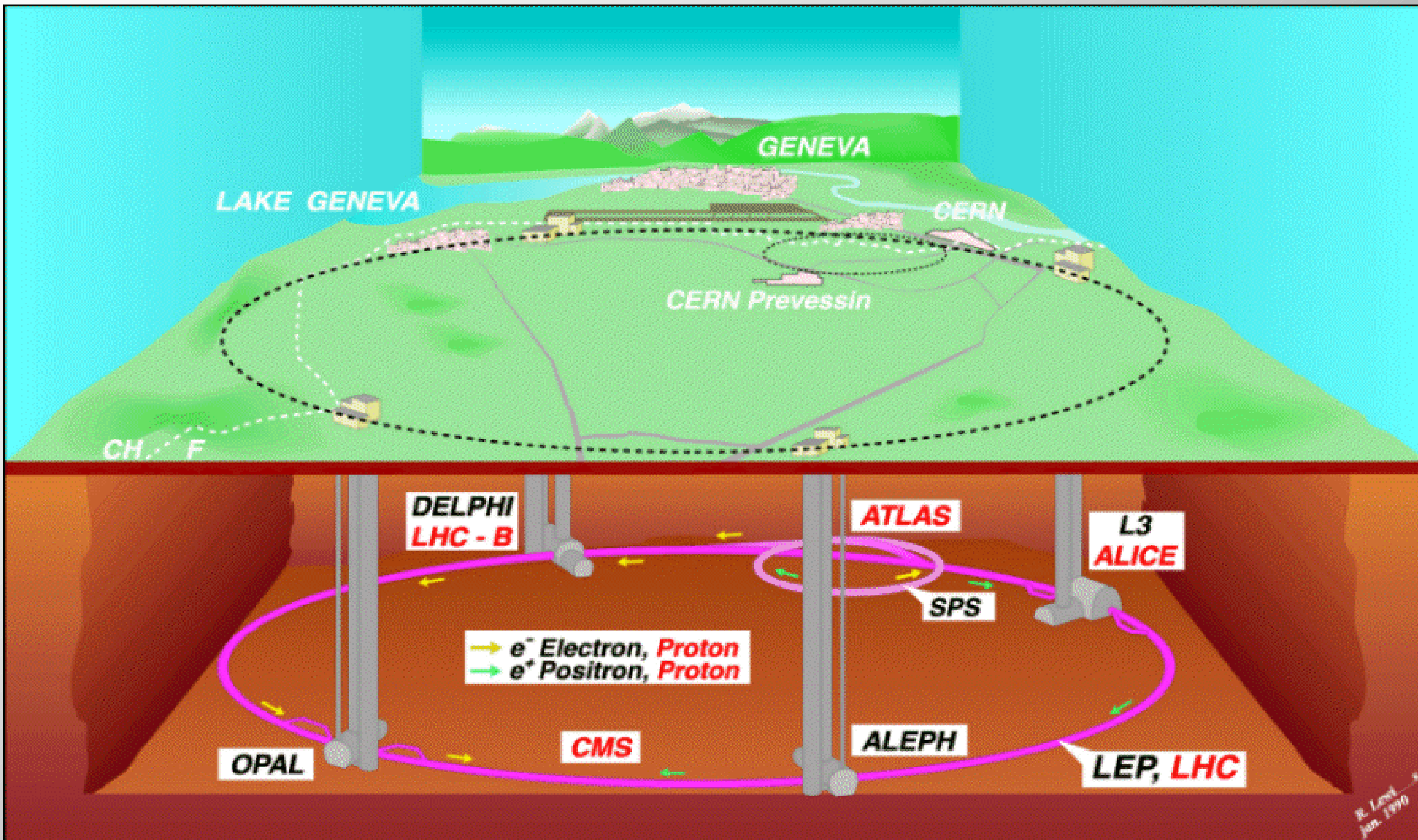
Superb performance of the accelerator and detectors (high luminosity) is essential

It won't be easy!

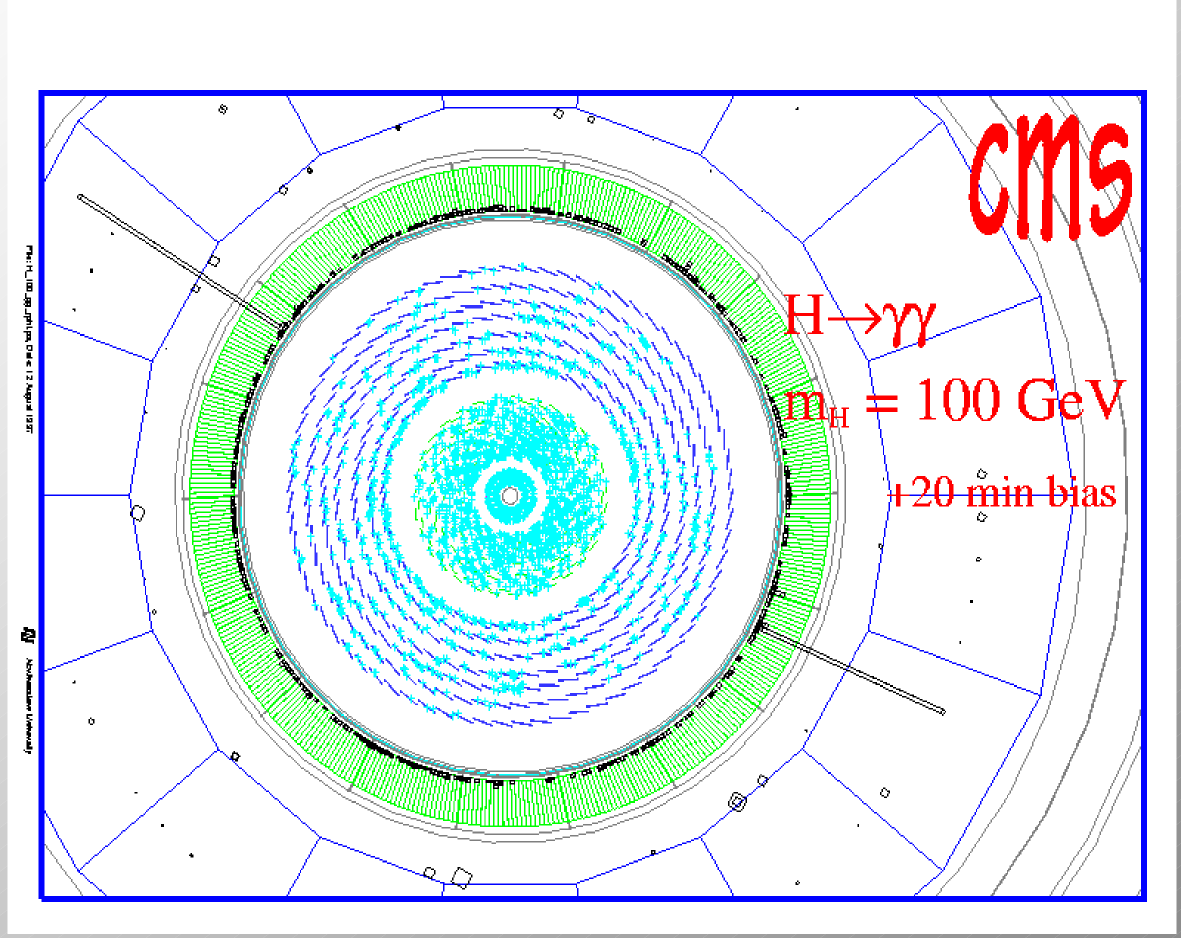


Higgs simulation courtesy of Joe Boudreau, CDF

The hunt for the Higgs will continue (from 2008 on) at the Large Hadron Collider (LHC) at CERN

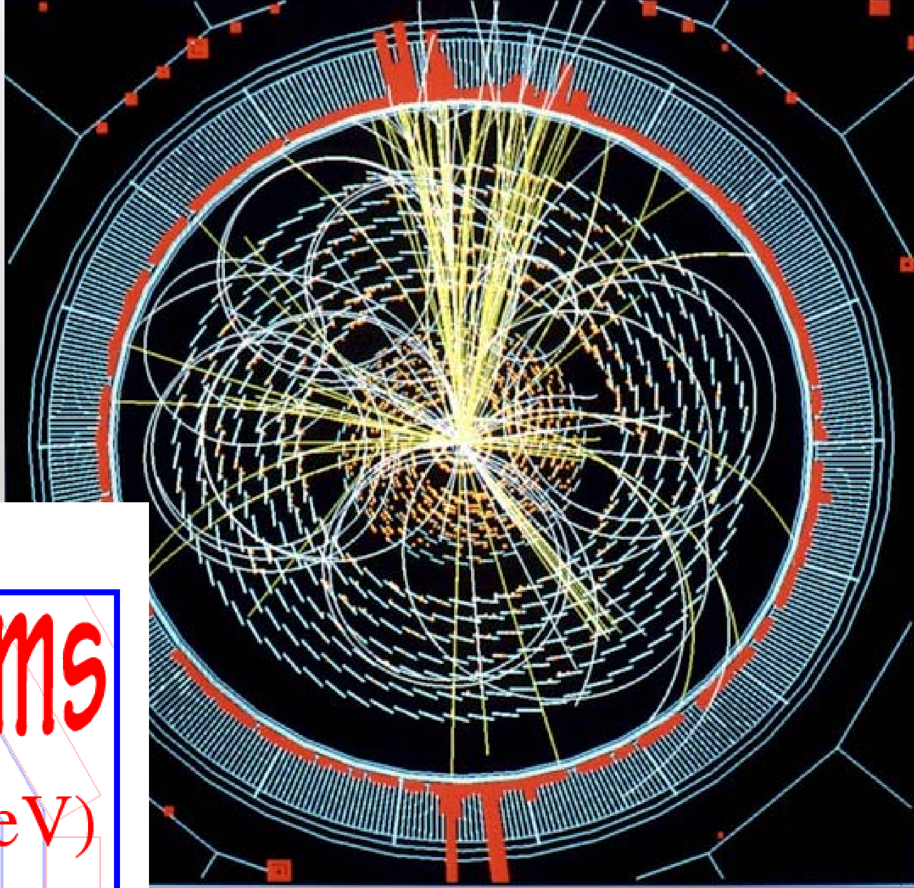


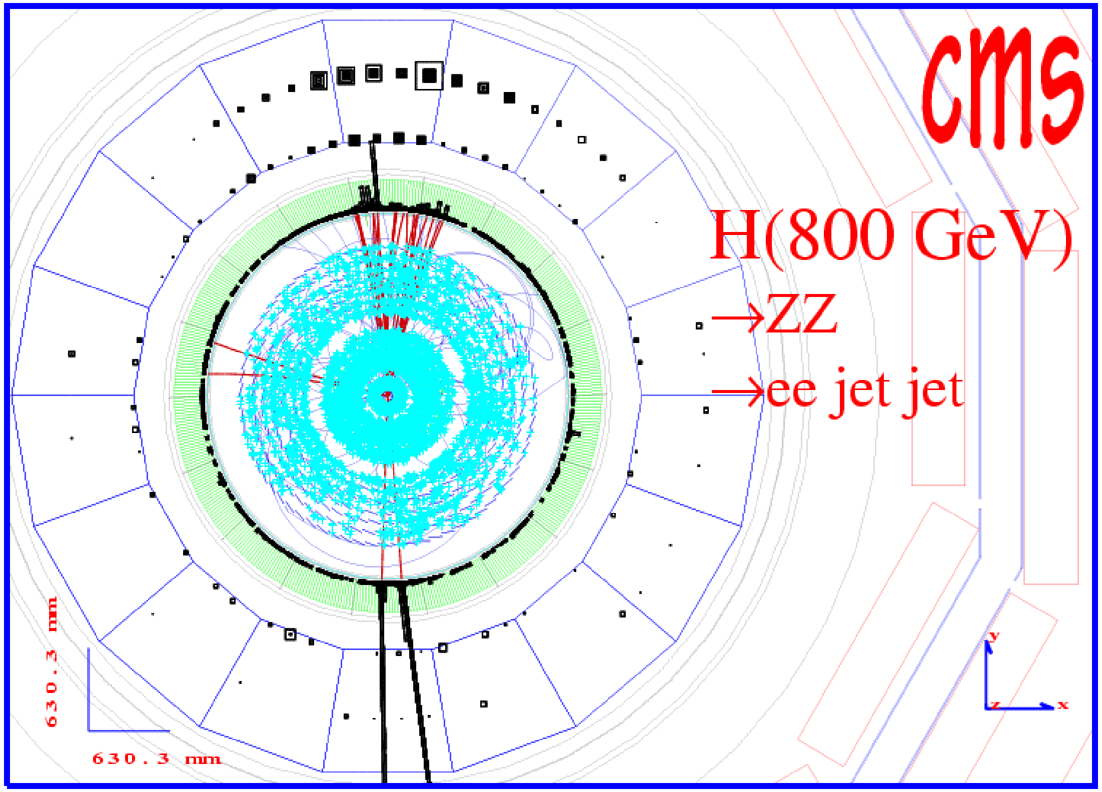
At LHC: many different possibilities to look for a Standard Model Higgs boson with mass up to about 1000 protons !



How will a Higgs with mass lighter than 140 protons look at LHC

How will a Higgs as heavy as 800 protons look at the LHC





If no Higgs is found at the LHC we will have to search for less beautiful explanations...

If the Higgs is found at the Tevatron and/or the LHC

$\Downarrow$

- **It can be a Higgs with Standard Model properties**

- **It can be a Higgs with peculiar properties,**
- **or multiple Higgs bosons**
- **or Higgs particle/s plus more particles**

The Standard Model gives a good description of the physics we have tested at experiments,

but, there are good reasons to believe that this is an effective description valid up to some high energy and that new physics exist

The Standard Model does not explain :

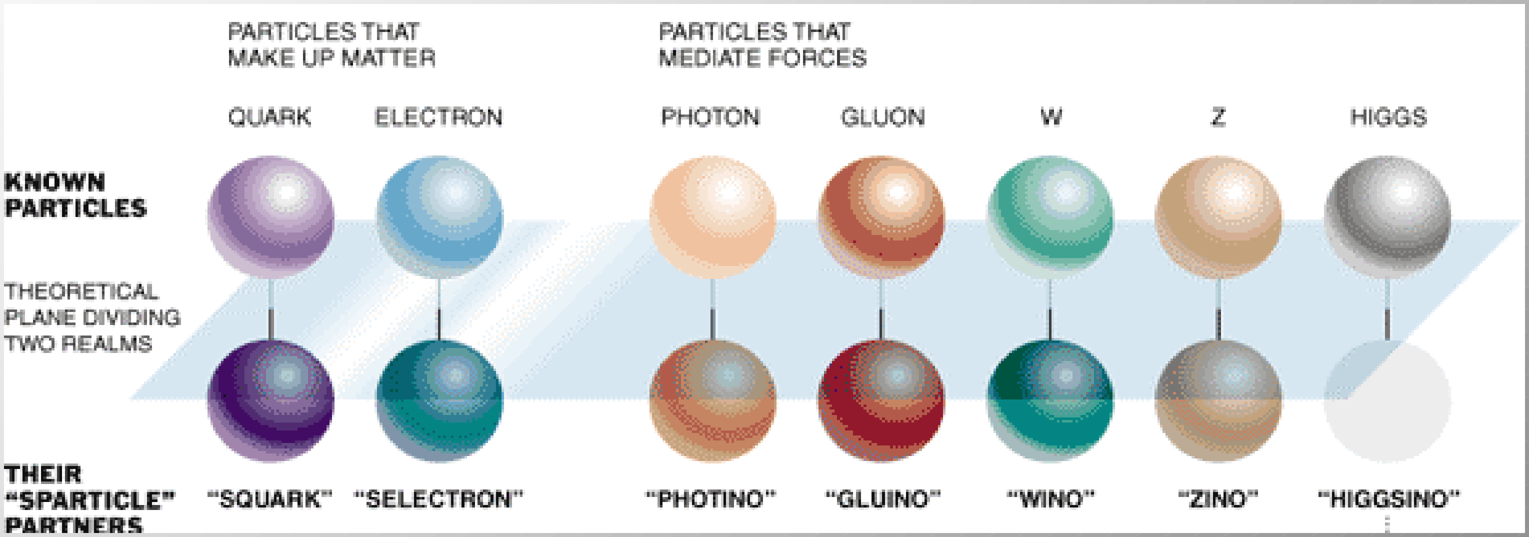
- **gravity**
- **the origin of the Higgs field**
- **dark matter**

It also has some inelegant mathematical issues

It does not allow for the unification of all forces in nature

supersymmetry

fermions ⟷ **bosons**

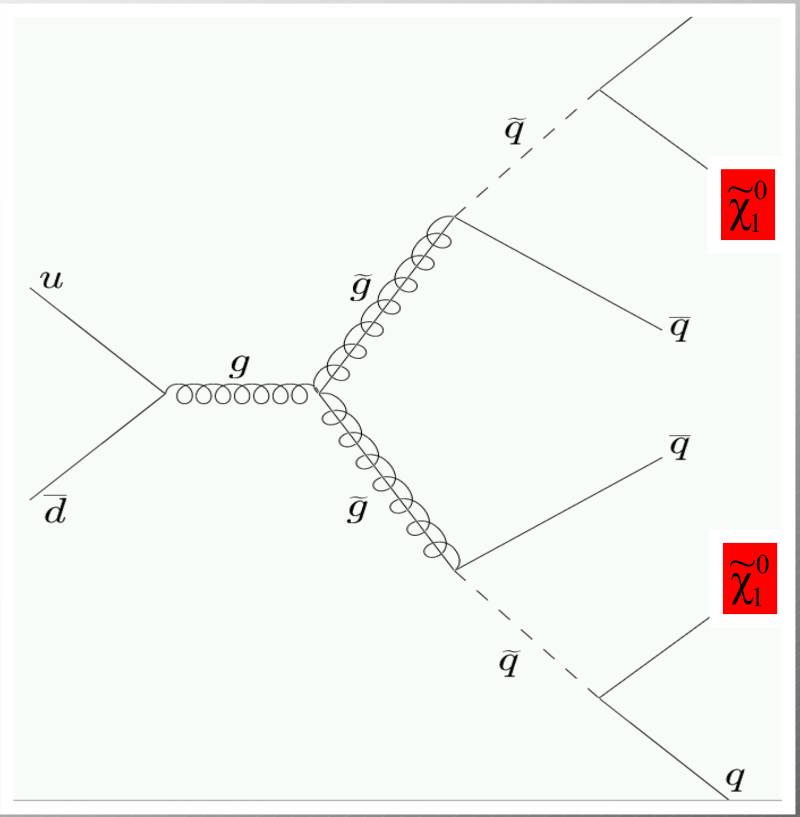


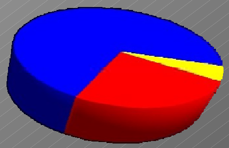
- none of the sparticles have been discovered yet
- it demands at least 4 different Higgs particles

Higgs Physics ⟶ Powerful test of SUSY

Supersymmetry at colliders

gluino and squark particles: production and decays

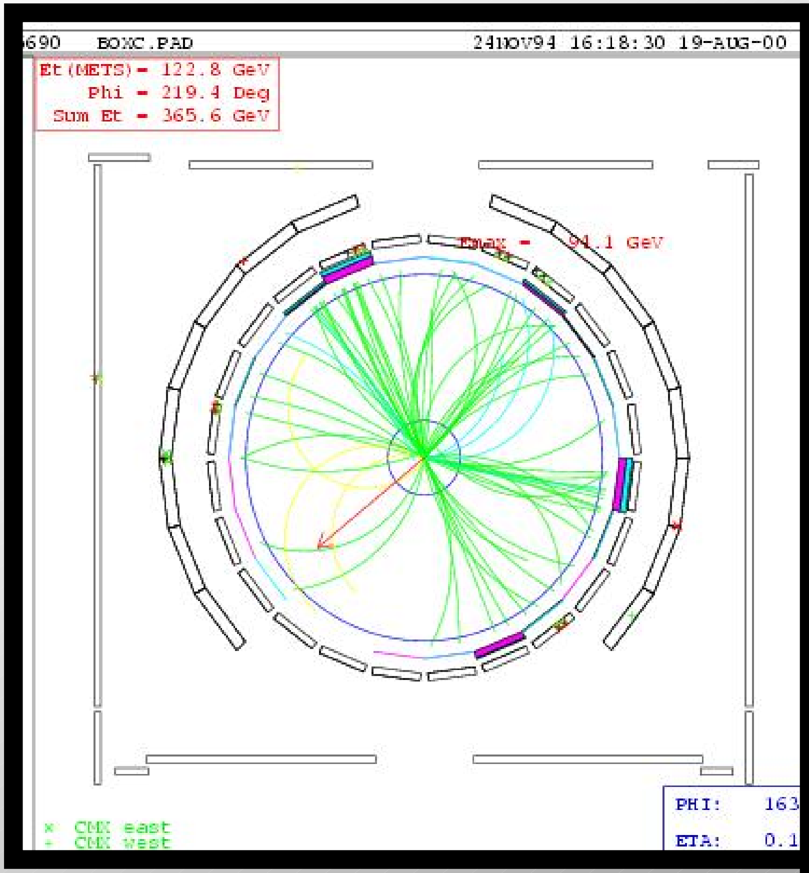


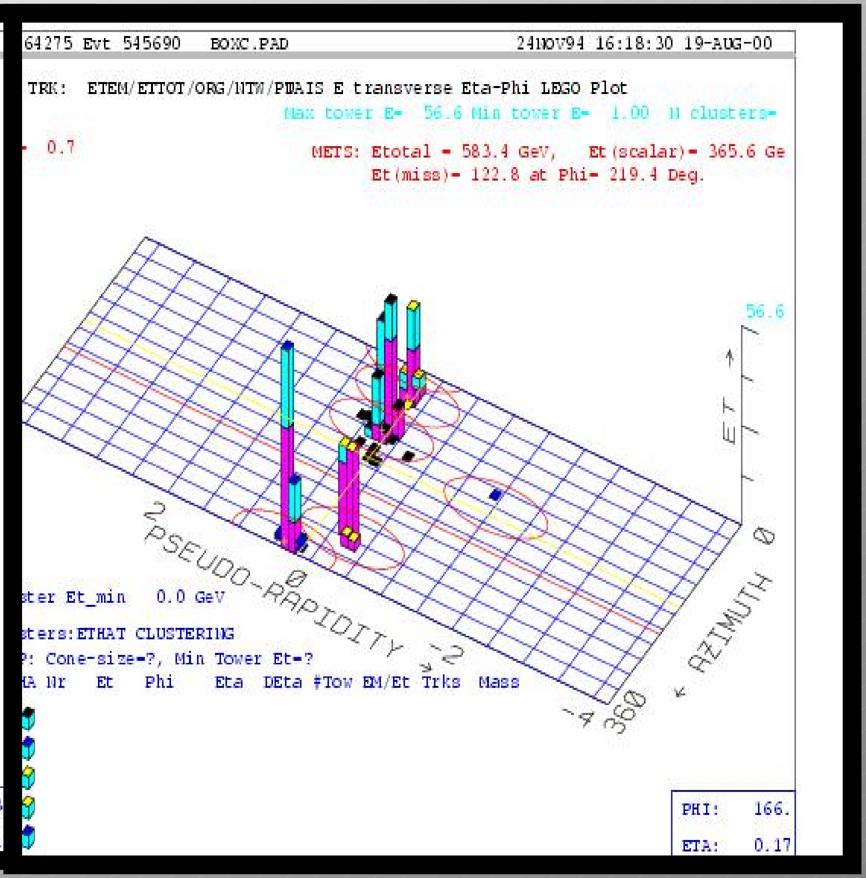


Is this the dark matter?

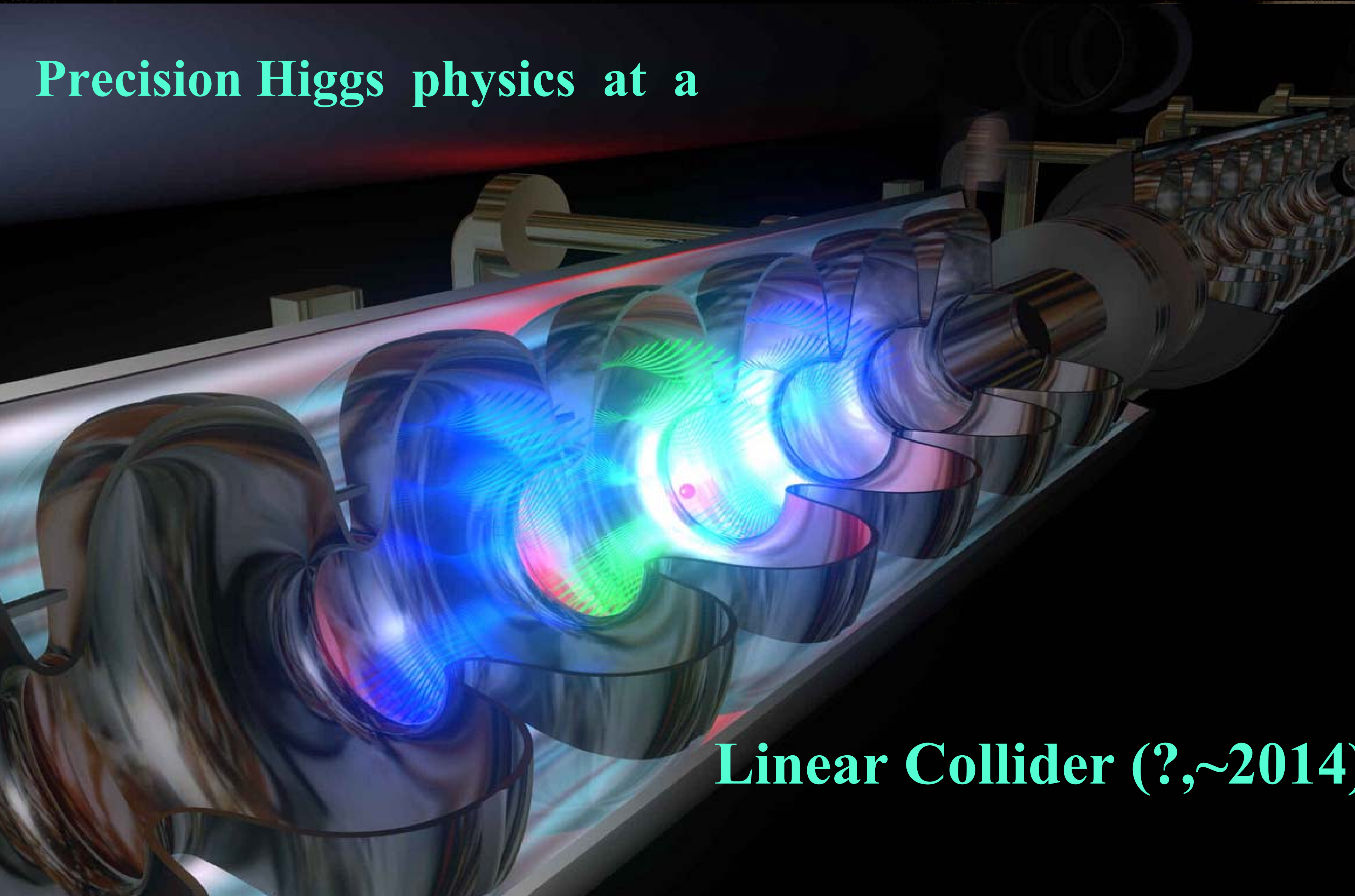
- most of the dark matter in the universe maybe the lightest sparticle

e.g.
SUSY candidate event at CDF





new accelerators for new physics



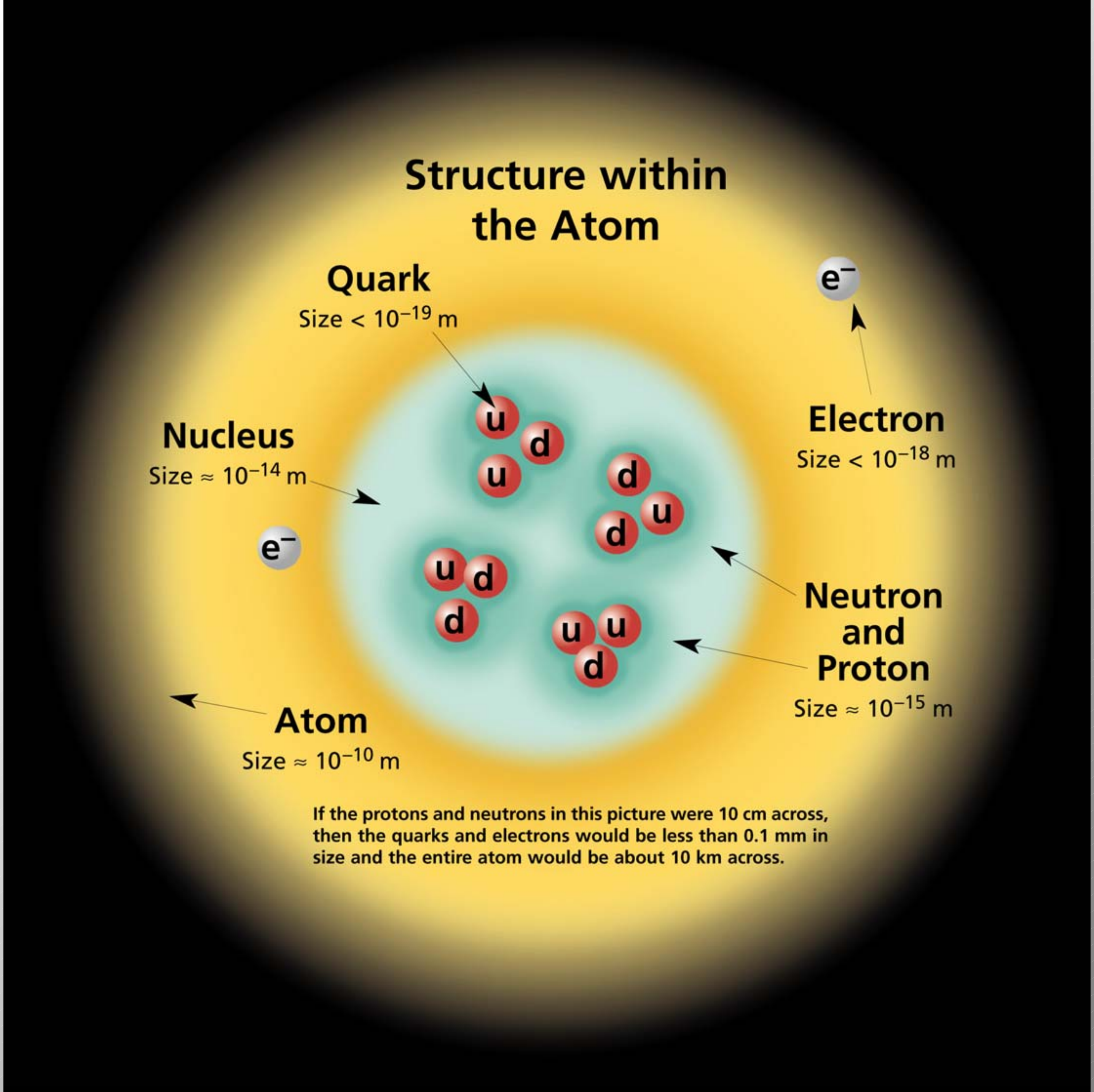
The high energy physics collider program around the world is crucial to pursue our understanding of nature

- ***We need to test the applicability of the Standard Model to higher energies***

- ***We need to answer questions beyond it:***
Gravity, dark matter, unification of all forces

- ***We need to understand the origin of mass***

Discovering the Higgs will be the first big step!


Structure within the Atom
Quark
Size < 10^{-19} m
e⁻
Electron
Size < 10^{-18} m
Nucleus
Size ≈ 10^{-14} m
u
d
u
d
d
u
e⁻
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.